U.S. NAVAL MEDICAL FIELD RESEARCH LABORATORY

CAMP LEJEUNE, NORTH CAROLINA

Vol. XIX, No. 1 January 1969

BODY ARMOR IN A HOT HUMID ENVIRONMENT
Part II: Studies in Heat Acclimatized Men

by

W. E. Yarger, LCDR MC USNR
and
B. D. Litt, A.M. (NMDSC, NNMC, Bethesda, Md.)
R. F. Goldman, Ph.D. (USARIEM, Natick, Mass.)

Bureau of Medicine and Surgery, Navy Department
Work Unit MF12.524 007-8008.2

49

Vol. XIX, No. 1 January 1969

BODY ARMOR IN A HOT HUMID ENVIRONMENT
Part II: Studies in Heat Acclimatized Men

by

W. E. Yarger, LCDR MC USNR

Physiology Division
NAVAL MEDICAL FIELD RESEARCH LABORATORY
CAMP LEJEUNE, NORTH CAROLINA

and

B. D. Litt, A.M.
National Naval Medical Center
Bethesda, Maryland

R. F. Goldman, Ph.D.
U. S. Army Research Institute of Environmental Medicine
Natick, Massachusetts

Bureau of Medicine and Surgery, Navy Department
Work Unit MF12.524.007-8008.2

Submitted by:

PHILIP J. RASCH, Ph.D.
Chief
Physiology Division

Approved by:

JESSE F. ADAMS
CAPT MC USN
Commanding Officer

SUMMARY PAGE

THE PROBLEM

Standard issue (M1955) personnel body armor is a heavy garment which markedly impedes cooling due to evaporation of sweat. Because of these characteristics, its use in a hot humid climate may lead to heat illness and to a decrease in military performance. This study, in heat acclimatized men, attempts to define those climates where armor will exert the most serious effects. It also reports these effects in terms of heat storage as a function of climate, uniform, time, and work rate.

FINDINGS

Wearing body armor causes more significant differences in heat storage in moderately stressful environments (WBGT 82-88°F). Below this level, evaporative cooling is so efficient that little or no significant heat storage occurs. Above this level, the environmental stress is so great (due mainly to markedly reduced capacity to evaporate sweat) that tremendous heat storage occurs irrespective of wearing body armor.

RECOMMENDATIONS

1. In environments such as these, serious consideration must be given to balancing the ballistic protection achieved by wearing armor against the increased risk of loss of some men due to heat illness, and decreased performance of others who are not incapacitated but who are operating under levels of increased stress. The object of this consideration should be to maximize the number as well as the performance of the men remaining.

2. When body armor must be worn in environments known to be stressful, attempts must be made to decrease the amount of heat which men are producing by (a) decreasing the load carried, and (b) slowing the pace.

3. Further studies to delineate the added effect of a solar caloric burden should be undertaken.

ADMINISTRATIVE INFORMATION

Bureau of Medicine and Surgery, Department of the Navy, Work Unit MF12.524.007-8008, report No. 2. Interim report. Approved for publication 16 December 1968.

We would like to acknowledge especially the many contributions of HM2 B. W. Mullins, USN, and SGT R. Dolensky, USMC, for their many hours of work in the environmental chamber and in calculating the many statistics.

In addition, we would like to thank Major J. E. Page, USMC; ENS T. W. Fetter, MC, USNR; Mr. R. Jackson; Mr. J. W. Hamby; Mr. H. G. Burns; and Mr. M. G. Moore, without whose efforts and interest this study could not have been conducted.

Mr. Litt is the Statistician at the Naval Medical Data Services Center, National Naval Medical Center, Bethesda, Md. Dr. Goldman is the Director, Military Ergonomics Laboratory, U. S. Army Institute of Environmental Medicine, Natick Laboratories, Natick, Mass.

[redacted]

This restriction will be removed and the report may be released on 28 February 1969.

ABSTRACT

The standard issue Marine Corps personnel body armor vest (M1955) was tested for its effect on men working under hot humid conditions approximating those seen in Southeast Asia. This vest is largely impervious to the passage of water vapor and thereby impedes evaporative cooling over the chest. Body armor produces a pronounced effect reflected by an increase in rectal temperature in the subjects when they are wearing the armor. This effect is restricted to a range of environment bracketed by 82-88°F WBGT (approximately). Below this level, heat loss from areas other than the chest is sufficient to dissipate body heat effectively. Above this range, the stress of the environment is so great and the evaporation of sweat is so inefficient that wearing body armor makes little difference. The effect of wearing armor in this range (82-88°F) is equivalent to a 5°F increase in the WBGT for unarmored men. The experiment was designed to eliminate the weight of the armor as a source of difference.

BACKGROUND

In this era of rapidly advancing technology we have changed from a man-oriented to a machine-oriented society. With increasing sophistication of our devices, we have too often tended to evaluate the technical effectiveness of these objects without considering their effect on man. An example is the widespread tendency to evaluate personnel body armor primarily in terms of its ballistic protection. We acknowledge, in a vague fashion, that wearing body armor has some impact on the man by compromising between the weight and ballistic protection of the armor. The fact that there are aspects other than weight to body armor which may be deleterious, if recognized, is usually held to be unimportant. The object of this study, and of several previous ones, is to point out the necessity of including in studies of military clothing systems their effects as well as their effectiveness.

In a previous study,[1] we investigated the effects of a single environment (WBGT 87.3°F) on unacclimatized men walking at 3 miles per hour. Under these conditions, 77% of the subjects could complete a full 90-minute march when they did not wear body armor; when body armor was worn, less than 40% of the men could complete the full 90 minutes. The study was limited to only two exposures, one with and one without the body armor in the single test environment, to preserve the "unacclimatized" state of the subjects. Any difference in performance associated with the weight of the armor *per se* was eliminated by adding an equivalent amount of lead to the subject's cartridge belt when he did not wear armor.

Military commanders should be able to predict the potential stress on their men imposed by wearing body armor over the spectrum of environments to which they might be exposed. In the current investigation, three environments have been studied in an attempt to define the effect of body armor over a range of environmental parameters. In such a study, it is important to present the results in such a fashion that they can be translated into terms of human effectiveness by the military commander. The statistical procedures necessary to interpret the results in such terms become quite complex; however, they are interesting because of the additional insight that they may give. In order to present the results clearly, the statistical procedures and their implications are presented in detail apart from the general results. However, the conclusions are derived both from the general and the complex analyses.

METHODS

These studies were conducted in the climatic chamber of the Naval Medical Field Research Laboratory, Camp Lejeune, North Carolina, during July and August 1968. Volunteers from the base brig, Camp Lejeune, who had

been in the local area for a minimum of three months prior to the experiment served as subjects. Three groups of eight men were studied; the ambient temperature and the customary work rates of these subjects were sufficient to consider these men heat acclimatized. The presentation of the three test environments was varied for every group; only half of the subjects wore armor on any particular test day to eliminate bias introduced by any further acclimatization induced as a result of the experiment.

The men walked at $3\frac{1}{2}$ mph on a motor-driven treadmill for up to 90 minutes. In an effort to remove the weight of the body armor as a confounding variable in the experiment, 10 extra pounds of lead were carried by the men on the days when they were not wearing the armor. Each subject wore a standard Marine Corps utility uniform, combat boots, a helmet and liner, and a cartridge belt, and each carried two full canteens and an M14 rifle. The weight of this load, along with that of the body armor or the equivalent amount of lead necessary to bring the total load to 57 pounds, is listed below:

Non-variable load:		
Utilities and boots	2.5 kg (5.5 lb)	
Two bandoleers with lead fill	7.2 kg (16.0 lb)	
Helmet	1.35 kg (3.0 lb)	
Rifle	4.1 kg (9.0 lb)	
Belt and canteen	2.7 kg (6.0 lb)	
Subtotal	17.85 kg (39.5 lb)	
Variable load:		
	Men with Armor	Men without Armor
Armor	4.5 kg (10 lb)	0
Extra lead filler	3.6 kg (8 lb)	8.1 kg (18 lb)
Subtotals	8.1 kg (18 lb)	8.1 kg (18 lb)
Total load:		
Non-variable	17.85 kg (39.5 lb)	
Variable	8.1 kg (18.0 lb)	
Total	25.95 kg (57.5 lb)	

Three skin temperature sites (calf, chest and forearm) were measured using 12-mm disk thermistors which were sewn onto 2-inch squares of copper screen backing; these were held in place by nonconstricting elastic ties. The rectal temperatures were detected with vinyl-covered thermistor probes inserted 10 cm into the rectum. Skin and rectal temperatures were measured and recorded on a data reduction system built for this laboratory.[2]

The three skin temperatures were weighted and summed according to the method of Burton[3] to obtain a mean skin temperature ($\overline{Ts}$). One third of a man's mean skin temperature was added to two thirds of his rectal temperature in calculating a mean body temperature ($\overline{Tb}$). Body heat storages were calculated by the formula:

$$\Delta S = 0.83 \times m_b \times \Delta Tb$$

where ΔS is the heat storage in kcal, 0.83 is an empiric constant for the specific heat of body tissues, m_b is the subject's initial nude weight in kilograms, and ΔTb is the change in mean body temperature calculated from the start of the march.

When subjects are dressed and transferred from a cool environment immediately into a hot test environment, large changes take place in the mean skin temperature; this causes a marked increase of ΔTb and ΔS during the initial 15-20 minutes.[4] Since this is not representative of real situations where armor is used, the subjects were dressed and allowed to rest in the heat chamber for a period of approximately 30 minutes prior to starting each experiment. This procedure allowed the skin temperature to come to a resting equilibrium with the environment.

Subjects were weighed nude at the start and end of each experiment. The difference between these two weights, corrected for all intake and output during the experiment, equals their total sweat production. In a similar manner, the subjects and all the gear they were wearing or carrying were weighed before and after the experiment. The difference between these two clothed weights, also corrected for intake and output, can be assumed to equal the total sweat evaporation. Therefore, one way in which the efficiency of the sweat evaporation process can be expressed is as total sweat evaporation divided by the total sweat production multiplied by 100 (i.e., percentage of sweat evaporation).

Metabolic heat production rates were measured at three times during the march, during the 10th to 20th, 40th to 50th, and 70th to 80th minutes. During these periods, nasal breathing was occluded and the subjects' expired air volume was measured with a Max-Planck respirometer. Two-way, low resistance (8 mm H_2O) valves were used to direct the respired air. A 0.3% sample of each expired breath was collected and, after drying, analyzed for oxygen content with a Beckman E2 paramagnetic oxygen analyzer. The volume of expired air, corrected to standard conditions, and the percent of oxygen in the dry gas were used to calculate the metabolic rate according to the method of Weir.[5]

No subject had eaten for at least 2 hours prior to being tested. The subjects were given 250 cc of water to drink every 10 minutes to reduce the

extracellular volume depletion which follows large losses of sweat. The subjects were marched at the same time each day to reduce effects attributable to circadian changes. Since treadmill walking in the heat frequently produces blisters, if these occurred and made walking difficult or changed a subject's style of walking, the man was dropped from the study.

GENERAL RESULTS AND DISCUSSION

Rectal Temperatures

There are a number of questions one must raise in the discussion of rectal temperatures in this experiment. Foremost, of course, is the question of the average rectal temperature after a given time interval, as a function of all the factors of the experiment which might be expected to produce some effect. In its simplest analysis, a change in rectal temperature represents the balance between heat production from work and heat lost to (or gained from) the environment. The experimental design in this study attempted to minimize differences in heat production, thereby leaving the factors which affect heat exchange with the environment as the major determinant of rectal temperature changes.

It is desirable to know the mean rectal temperature as a function of time, temperature and clothing because as an individual passes a rectal temperature of 39.5°C, his chances of becoming a heat casualty increase greatly. In our experiment, whether or not symptoms and signs of heat exhaustion had occurred, an individual was declared a heat casualty when his rectal temperature reached 39.5°C. However, the time which an individual requires to reach this point depends not only on how fast his rectal temperature rises, but also on his starting rectal temperature. This being the case, differences in starting rectal temperature may produce significantly different tolerance times where tolerance time is defined as the amount of time to become a heat casualty. This raises the very important question of the relationship of the mean and variance of the starting rectal temperature (Tr_0) of our sample to the population in general. (See Statistical Section.)

The values of rectal temperature at 25, 45, and 90 minutes have been adjusted by analysis of covariance (see Statistical Section) for differences in starting rectal temperature. These adjusted mean rectal temperatures are presented in Table 1 as a function of time, environment, and body armor.

The data reveal that the effect of wearing body armor is most significant at the least stressful environment (WBGT 82.4); i.e., the effect of body armor is felt most in those environments where sweat evaporation is relatively efficient. The more severe environments are already so stressful that the effect of the body armor is difficult to detect. This is very apparent in the graphical

Table 1

Rectal Temperature† (°C)

Time (min)	Armor	WBGT Levels (°F)		
		82.4	89.0	95.9
0	Without	37.28	37.18	37.34
	With	37.21	37.09	37.52
25	Without	37.74	38.04	38.70
	With	37.84*	38.09	38.65
45	Without	37.92	38.69	-
	With	38.17*	38.79*	-
90	Without	38.29	-	-
	With	38.64*	-	-

† Rectal temperatures at 25, 45, and 90 minutes are adjusted by analysis of covariance for differences in individual initial values of rectal temperature. (See Statistical Section.)

* Implies a significant difference. ($p < .05$) (See Statistical Section.)

presentation of these results in Figure 1. There is no data on the men at 90 minutes when the WBGT is 89°F, nor any for 45 or 90 minutes when the environment was 95°F WBGT since insufficient numbers of subjects completed these conditions.

It should be stressed that Figure 1 is a graph of treatment effects; i.e., group mean rectal temperatures under the various conditions of time, environment, and body armor, and does not necessarily imply continuous data. There are two noteworthy items in Figure 1: the first is the increase in the rate of rise of rectal temperature as the severity of the environment increases; it can also be seen that there is a wide spread between the rectal temperatures with and without body armor at the lowest environmental condition as well as a difference in the rate of rise. However, there is very little difference in either the rate of rise or the absolute temperature levels at the more stressful conditions where sweat evaporation _per se_ is less efficient.

The data on change in rectal temperature (ΔTr) from this experiment have been combined with that from our previous study[1] and is shown in Figure 2. Several interesting trends are revealed. First, comparison of the men without armor at 87.3°F with the men with armor at 82.4°F indicates that at this level,

wearing armor constitutes a stress roughly equivalent to a 5° rise in WBGT in unarmored men.

In addition, we see that there is a difference in the response to the 87.3° and 89° environment which appears more marked than a separation of only 1.7° in the WBGT should cause. However, these two environments are separated by the 88°F WBGT level which Yaglou and Minard[6] established as the upper limit for heavy work, thus confirming the physiological usefulness of this demarcation of environments. Perhaps this limiting value represents a point where the physiological adaptive mechanism of heat acclimatization is unable to deal with increasing environmental stress.

Admittedly one group (89°) represents acclimatized and one (87.3°) represents unacclimatized men, but if differences in acclimatization were considered, we should expect the acclimatized men (89°) to do better, thereby decreasing rather than increasing the difference in response in comparison with the unacclimatized (87.3°) men.

Fig. 1. Rectal Temperatures (°C)

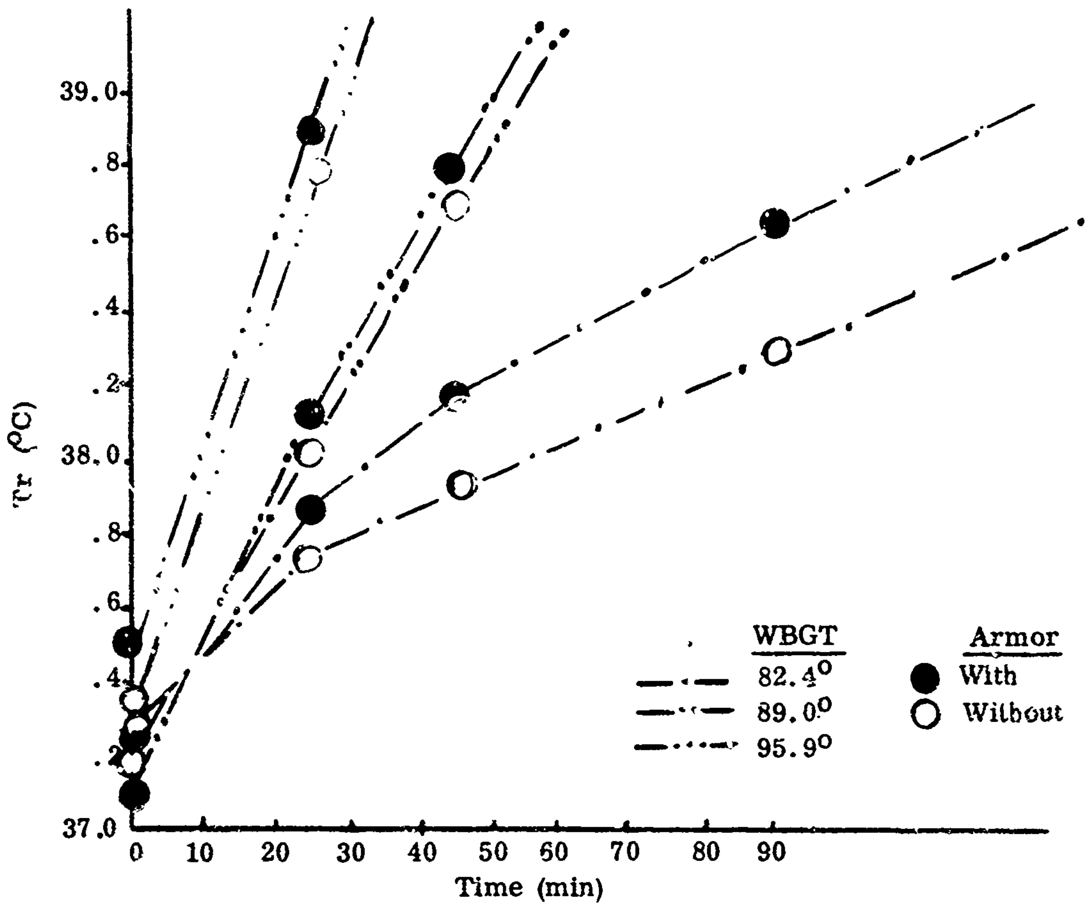
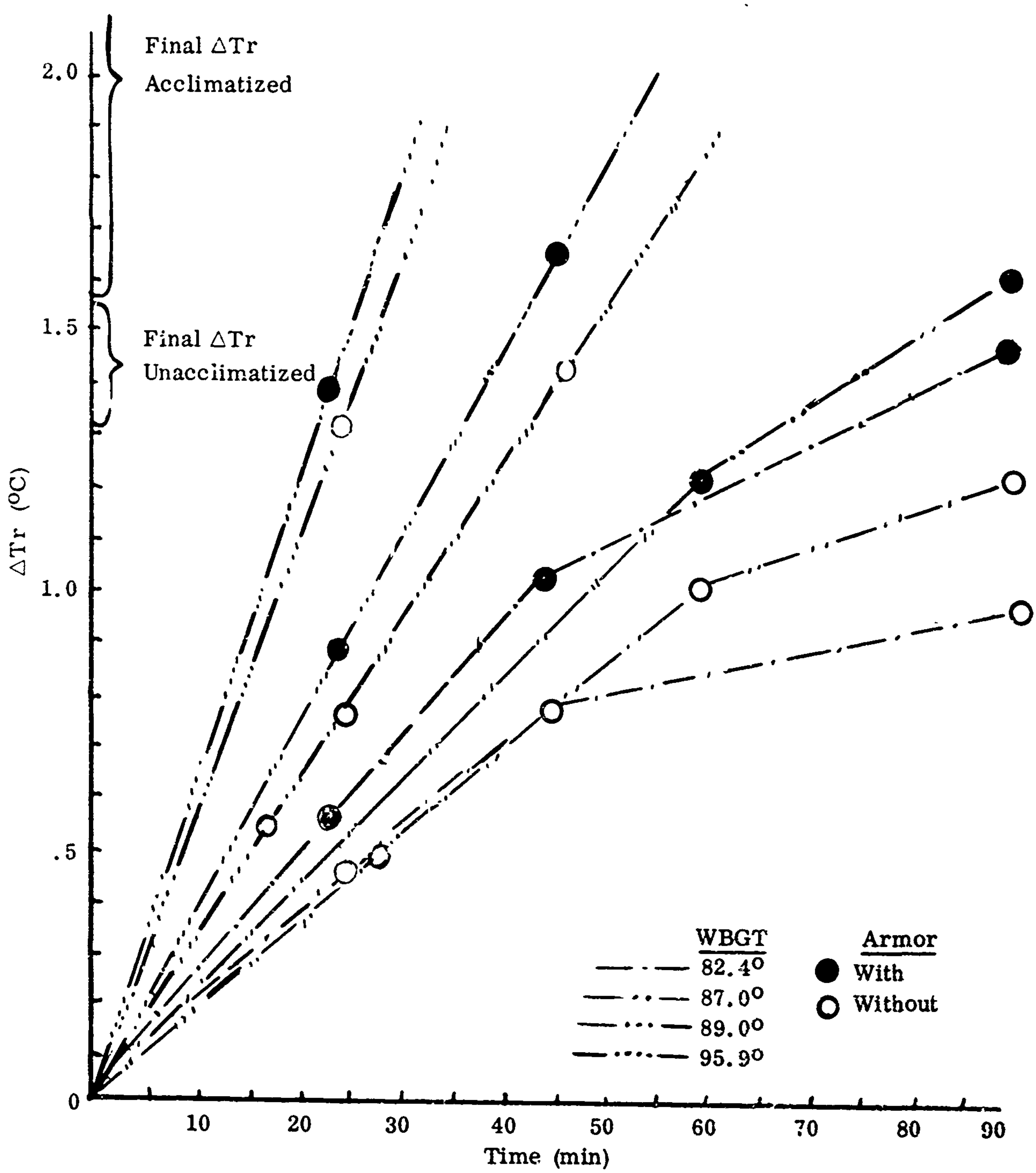


Fig. 2. Change in Rectal Temperature (ΔTr)



Skin Temperatures

The subjects were pre-exposed to the test environment as stated in the Methods section. This caused the desired increase in base line resting skin temperatures. In addition, body armor per se produced an initially higher skin temperature because in these environments sweat evaporation is required even at rest and body armor blocks this evaporation for the area it covers. The data on group mean skin temperature are presented in Table 2 and demonstrated graphically in Figure 3. The data indicate that at all times and under all conditions tested the mean skin temperature of the men wearing body armor is significantly hotter than that of the men without armor. Although the differences due to body armor are all statistically significant, a better appreciation of the magnitude of these differences, as well as their trends, can be seen in Figure 3.

We see that although the men wearing armor are always significantly hotter, the greatest difference is seen in the least stressful environment. Mean skin temperature appears to reach a plateau after about 45 minutes in the 82.4 WBGT environment. Although at 89 WBGT a change of slope is apparent at 25 minutes, this is probably not a plateau as the values continue to rise slightly. At 95.9 WBGT the slope is very steep with very little separation between the two lines representing the with and without body armor conditions.

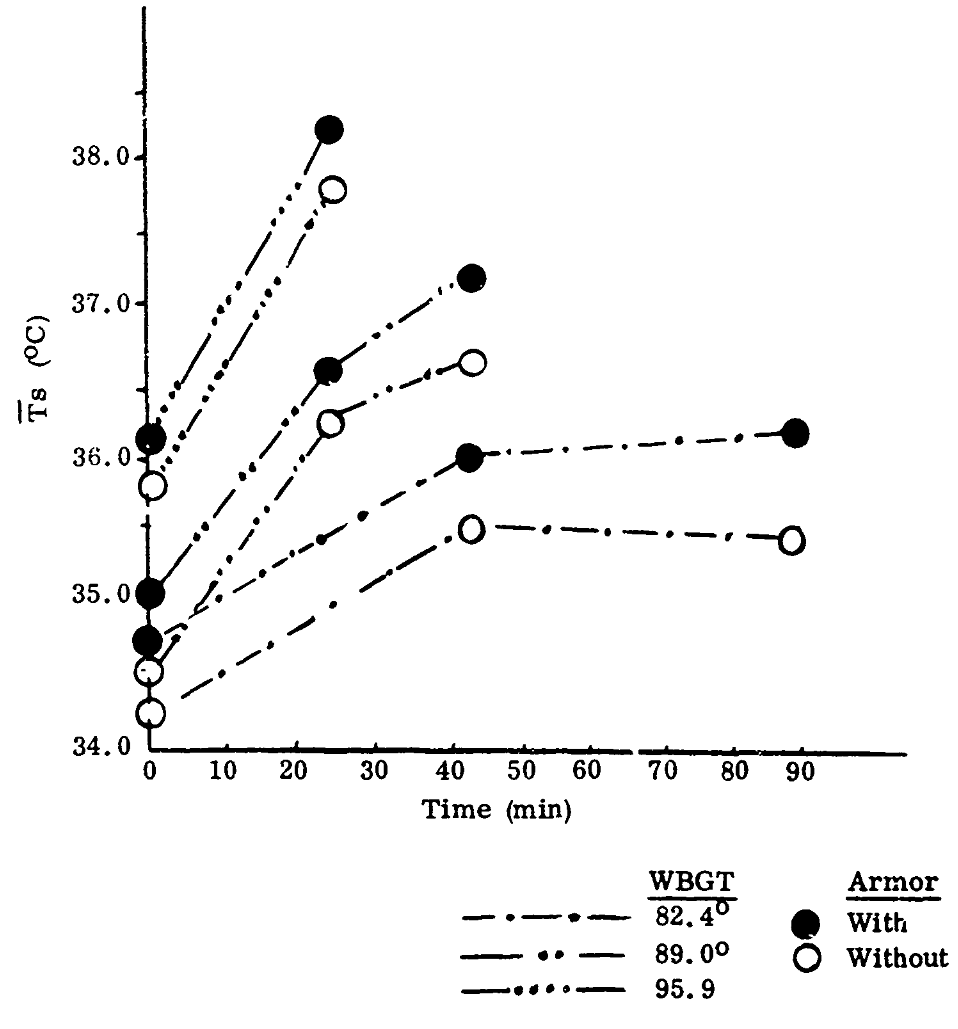
Table 2

Average Mean Skin Temperatures ($\vec{T}s$) (°C)

Time (min)	Armor	WBGT Levels (°F) 82.4	89.0	95.9
0	Without	34.25	34.62	35.86
	With	34.73*	35.11*	36.23*
25	Without	35.02	36.24	37.83
	With	35.72*	36.57*	38.22*
45	Without	35.56	36.63	-
	With	36.06*	37.21*	-
90	Without	35.48	-	-
	With	36.21*	-	-

*Significant difference ($p < .05$)

Fig. 3. Mean Skin Temperatures (°C)



Thus, with skin as well as rectal temperatures, body armor produces less difference in very hot and humid environments than in environments which are more moderate. Again, the decreased efficiency of sweat evaporation, associated with the increased content of water vapor in the air in the more stressful environments, diminishes the observed impact of the body armor. Indeed, in a saturated ambient environment hotter than a man's skin temperature, aside from the weight of the armor, it would probably have little effect on the man's tolerance.

Body Temperature

Mean body temperature is a derived function and, with only one formula used to compute it, will be inaccurate, particularly for non-steady state conditions. Despite it's inaccuracies, there are several reasons to compute it. It gives a combination of skin and rectal temperatures as an additional method of estimating tolerance time parameters, to compare with those based only on rectal temperature. In addition, it is essential in calculations of the heat balance equation and in any attempt to estimate the amount of heat the body can lose during exercise. Finally, since there is only a very small range of tolerable rectal temperatures, mean body temperature, incorporating both skin and rectal temperature, reflects the temperature gradient from skin to core. The magnitude of this heat transfer gradient from skin to core is probably a better indicator of the cardiovascular stress and danger of heat exhaustion collapse than any measure of core or skin temperature alone.

The calculated mean body temperatures are presented in Table 3 and indicate that the environmental differences in this study produce a highly significant effect in base line mean body temperature ($\overline{T}b$). This is due primarily to the contribution of mean skin rather than rectal temperature. There are no significant differences in base line values attributable to body armor. Body armor does produce a significant elevation in mean body temperature at all subsequent times tested at the 82.4° WBGT environment and, in addition, at 25 minutes at the 95.9° WBGT environment. The data on mean body temperature are presented graphically in Figure 4. Again, the greater magnitude of the effects of body armor at the less stressful environment can be readily observed.

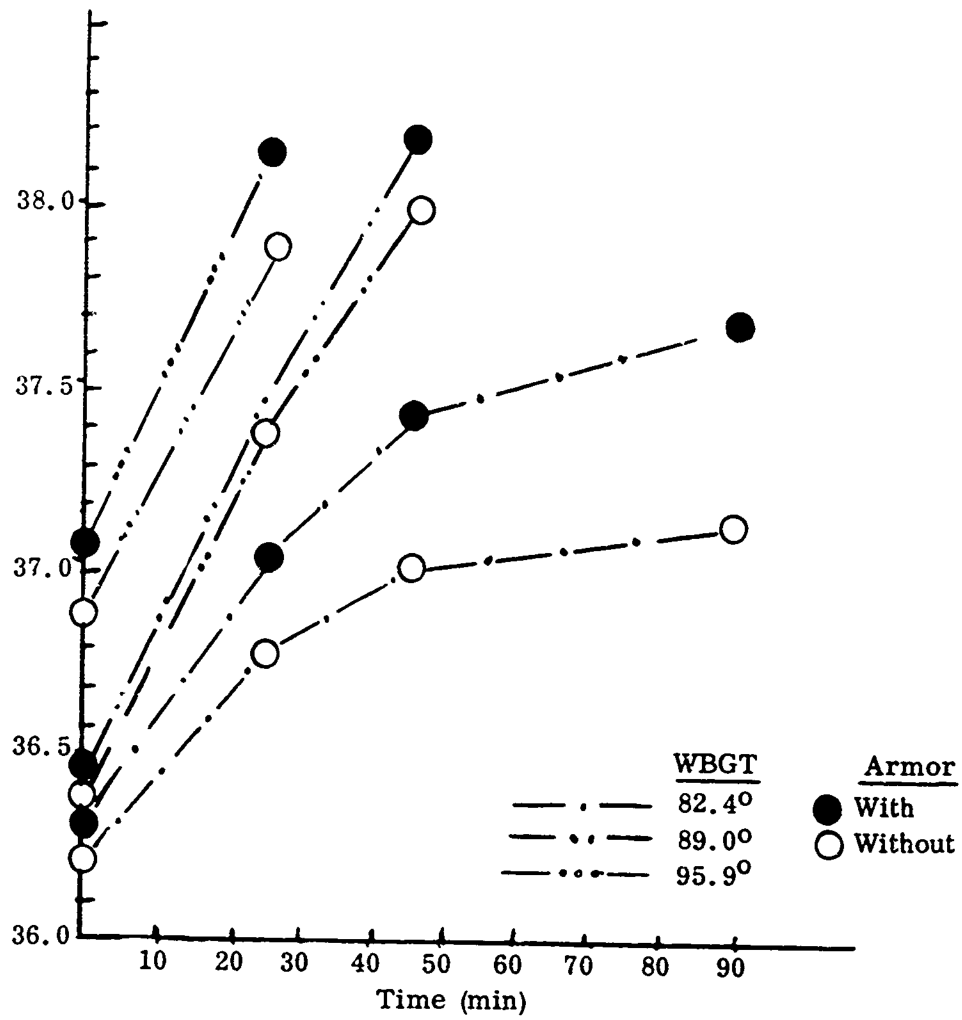
Table 3

Mean Body Temperatures (°C)

Time		WBGT Levels (°F)		
(min)	Armor	82.4	89.0	95.9
0	Without	36.19	36.39	36.87
	With	36.31	36.45	37.06
25	Without	36.77	37.37	38.37
	With	37.04*	37.48	38.64*
45	Without	37.01	37.97	-
	With	37.41*	38.18	-
90	Without	37.13	-	-
	With	37.67*		

*Significant difference ($p < .05$)

Fig. 4. Mean Body Temperature (^oC)



Body Heat Storage

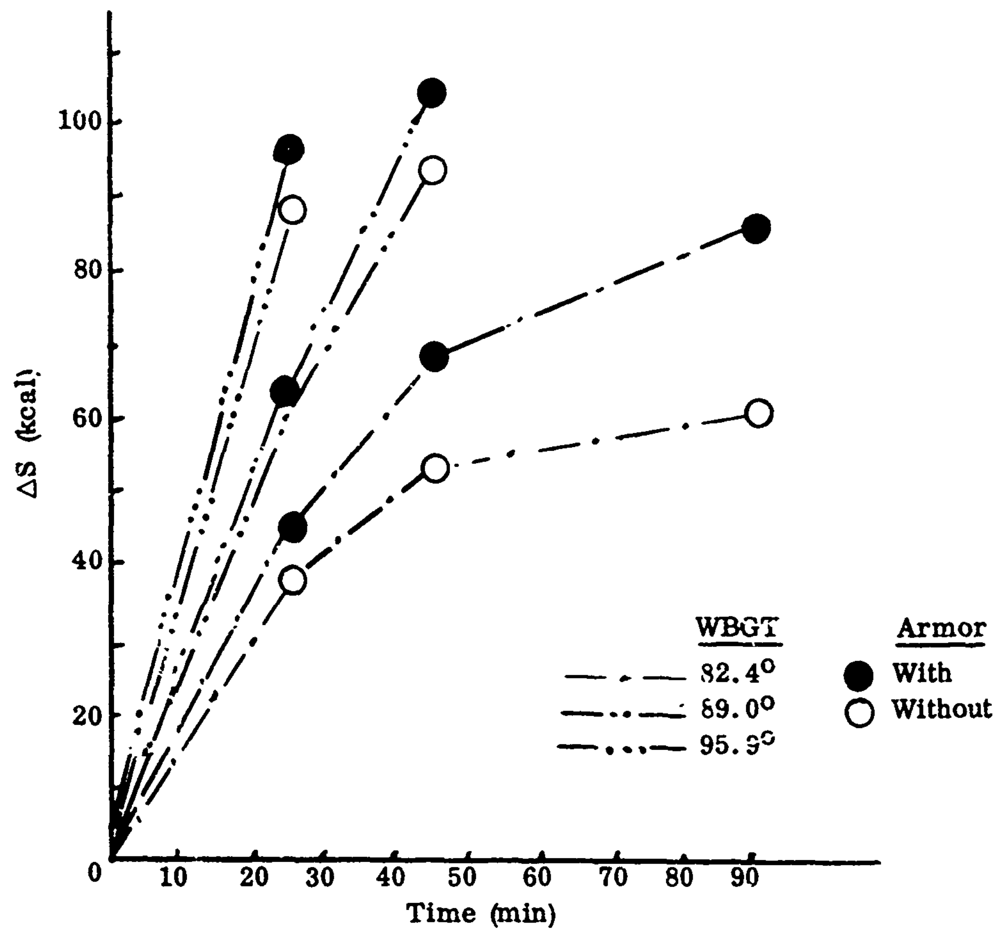
If heat production and heat loss were both linearly related to body mass, we could reasonably expect that changes in body heat storage would represent only a linear transformation of mean body temperature by the equation:

$$\text{Body heat storage} = 0.83 \times m_b \times \Delta T_b$$

The extent to which calculated heat storage diverges from a linear transformation represents the interplay of differences in body mass, which can be related to heat production in a fairly linear fashion, and body surface area, which is the

prime anatomical determinant in heat loss. Calculated mean body heat storage is presented in Figure 5. Comparison of Figures 4 and 5 shows that including this correction for differences in subject size decreases even further the observed effects of body armor at the more stressful environments; i.e., not only are differences in armor less important as the environment to skin vapor pressure gradient decreases, but also differences in body surface area become less important in heat dissipation.

Fig. 5. Heat Storage (ΔS) (kcal)



Sweat Evaporation

The evaporation of sweat in a clothed man is complex. Differences in sweat evaporation as a function of the environmental temperature and the amount of water vapor in the environment have been discussed above. Another environmental factor that plays a very significant role, but one which has not yet been well defined, is wind. It is generally known that wind affects both evaporative and non-evaporative heat transfer through clothing. While a formula is available for calculation of changes in non-evaporative heat loss as a function of wind velocity, a similar formula for evaporative heat transfer characteristics is not yet well defined.[7] In addition, a further complicating factor involves the nature of the air movement, i.e., whether flow is laminar or turbulent. In the present experiment, velocity was made uniform across the entire body profile; however, as a by-product of creating a uniform flow pattern, the wind pattern was changed from largely turbulent to largely laminar flow. Turbulence is always created, of course, when the wind strikes the subject, but it is possible that laminarizing the wind flow may decrease the amount of wind that is available for exchange with the air semi-trapped under the lower edge of the body armor vest.

We feel that the observed differences in tolerance of the 89° WBGT environment in this experiment, in comparison to our previous study in unacclimatized men at 87.3° WBGT, are due to several factors. Primarily, the difference reflects the actual severity of the environment, although the dry bulb temperature was the same in both studies (95°F). The difference in wet bulb temperature, 86.5°F here and 83°F wet bulb in the earlier study, reflects a difference of 4 mm Hg of water vapor pressure in the ambient air. Using an im/clo ratio of 0.22 with and 0.29 without armor, as measured on a sweating copper manikin,[7] this apparently small difference of 4 mm Hg vapor pressure represents a reduction in the ability to evaporate sweat in this study of 30 gm/hr with armor and 40 gm/hr without armor, with a resultant predicted extra heat storage of 23 and 18 kcal/hr respectively. In addition to these differences in water vapor pressure in these two studies, differences in wind flow patterns may also have played a significant role in decreasing the tolerance time of the men in this experiment, even though they were acclimatized.

The difference in observed tolerance at 89° WBGT compared to the 87° WBGT is most clearly demonstrated in the ability of the subjects to evaporate sweat, expressed as the percent of sweat produced which was evaporated (TSE/TSP ratio times 100). In the earlier study,[1] the men were able to evaporate 53% of their sweat when they were wearing armor, compared to 65% of their sweat when they were not wearing armor. In the current study, the mean percentage is 46.8% when men are wearing armor compared to 53.5% when they are not wearing armor. Thus, the higher vapor pressure in the environment in the present study produced a decrease in this ratio of approximately 11% in the

men not wearing armor and 6% in the men wearing armor; as anticipated, the decrease is more pronounced when sweat evaporation is not already impeded by the armor. This decrease almost certainly accounts for the shorter tolerance time found at 89°F WBGT in this experiment, even though these men were acclimatized.

Total sweat production rates are shown in Table 4, and the efficiencies (or percentage) of sweat evaporation in Table 5. Due to the effect of markedly different exposure times represented by these ratios, comparison of evaporation rates across temperatures is somewhat questionable, although it is justifiable to compare differences caused by body armor within temperatures.

Table 4

Mean Sweat Production (kg sweat/hr)

	WBGT Levels (°F)		
Armor	82.4	89.0	95.9
Without	1.620	1.560	3.105
With	1.780	1.815	3.515

Table 5

Efficiency of Sweat Evaporation (total sweat evaporation/total sweat production x 100 = % sweat evaporation)

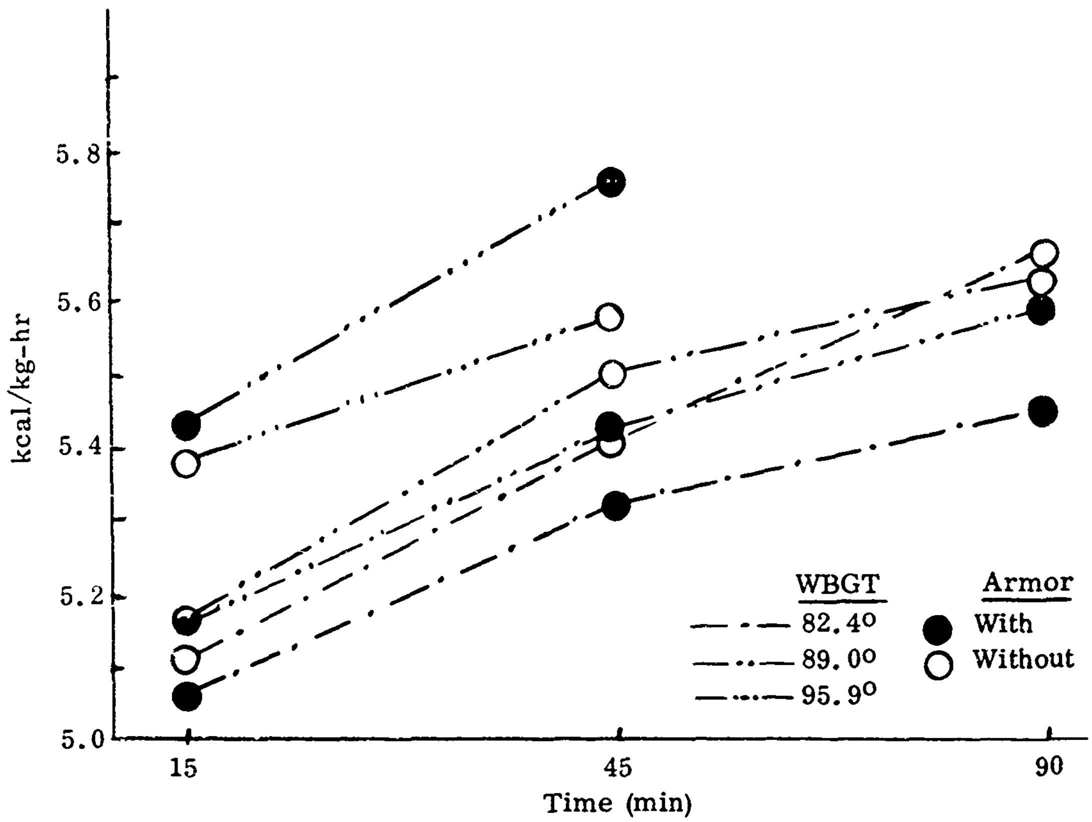
	WBGT Levels (°F)		
Armor	82.4	89.0	95.9
Without	63.8	53.5	36.6
With	56.1*	46.8	34.8

*Significant difference

Metabolic Rates

The data for metabolic rates are presented graphically in Figure 6. In addition to the expected rise in metabolic rate as a function of time, reflecting decreasing efficiency with increasing fatigue, there is a suggestion of an increase in metabolic rate as a function of temperature. Rather than reflecting a true

Fig. 6. Metabolic Rate



effect of high temperature on metabolic rate, this is probably a secondary effect of an increase in the rate of fatigue with very high environmental temperatures. (See Statistical Section.)

Tolerance Time

Tolerance time in these experiments is defined as the period a subject can remain in the chamber before becoming a heat casualty, with removal based on symptoms or on reaching a rectal temperature of 39.5°C. Quite clearly, if a subject remains in the chamber for the full 90 minutes of the test, this does not represent a limit to his tolerance time. In our previous study on unacclimatized men at 87.3° WBGT, sufficient numbers of subjects remained the full 90 minutes so that it was not valid to calculate a "tolerance time." Instead, the percentage of subjects who could remain the full 90 minutes was calculated.

In the current study, all subjects were able to last a full 90 minutes in the least severe environment, whether they were wearing armor or not. Thus, under the conditions of this study, no conclusions could be reached regarding tolerance times at a WBGT of 82.4°. However, very few men could complete the full 90 minutes when the WBGT was 89° and none at a WBGT of 95.9°; thus one can calculate tolerance times for these two conditions.

Tolerance times are presented as functions of environment and body armor in Table 6 and Figure 7. Although interpolation between the two points shown in the graph seems valid (because the range is narrow even though the relationship might very well be curvilinear rather than, as drawn, linear), it is incorrect to extrapolate the tolerance time data shown in the graph to derive a value for the 82.4° WBGT environment.

Although the difference in tolerance is statistically significant at 89° WBGT, the difference in tolerance times as a function of body armor is quite small. This is to be expected from the previously presented data which indicated that the fraction of the total stress contributed by body armor at these severe environments is relatively small in comparison to the effect of the environment itself.

Fig. 7. Tolerance Time vs. WBGT

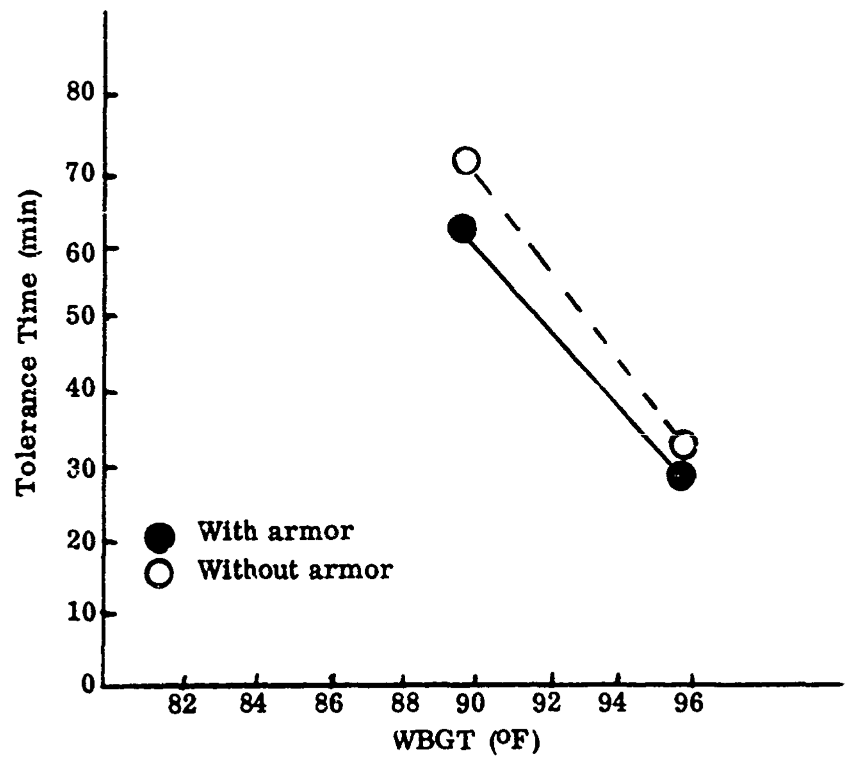


Table 6

Tolerance Time (min)

Armor	WBGT Levels (°F)	
	89.0	95.9
Without	71.3	32.3
With	63.0*	28.4

*Significant difference

STATISTICAL SECTION

Methods

Differences between test samples were tested by analysis of variance which was partitioned according to various experimental factors as indicated. F ratios significant at the .05 level are designated with an asterisk (*); those significant at the .01 level with two asterisks (**). Differences between treatment means were tested by the test of least significant difference (lsd) at the 5% level calculated as:

$$\underline{\text{lsd}}\ (.05) = t\ .05 \sqrt{\frac{2\ (s^2)}{r}}$$

where t .05 is Student's "t" at the .05 level for the error degrees of freedom, "s^2" the error mean square from the appropriate analysis of variance and "r" is the number of observations per mean. The lsd was used only to test differences in the means with body armor from the means without body armor. These differences were tested even if the F ratio for the body armor effect was insignificant, as these were all preplanned comparisons.[8]

As discussed later, in certain instances it was necessary to do an analysis of covariances; when this was done, the treatment means were adjusted[9] and the differences between the adjusted treatment means were tested by Finney's level of significant difference.[10]

To define the regression of the rise of rectal temperature as a function of time for each representative environment and for the two uniform configurations, we pooled the observations from all subjects, sampled at 5-minute intervals up to but not beyond 60 minutes. We then tested the regression within a given environmental level for body armor effects by testing the pooled error variances[11] where the F ratio tested was defined as:

$$F = \frac{SSE_{total} - (SSE_{with\ A} + SSE_{without\ A})}{SSE_{with\ A} + SSE_{without\ A}} \cdot \frac{df_{total}}{df_{total} - (dfw + dfw/o)}$$

In a study such as this, the question we are primarily interested in is the ability to predict how long men can tolerate a particular specified environment. Although there are many possible parameters that we could use to describe these situations, the most important when we are interested in the ability of men to tolerate hot environments are: environmental descriptors, work rate, uniform parameters, and state of acclimatization. Implicit in the choice of these parameters is the concept that the amount of heat a man can store in his body before becoming a heat casualty is, at least for the individual, a fairly narrowly defined quantity. Thus we have chosen those parameters which relate to an individual's heat production and those which determine his ability to dissipate that heat to the environment. Examination of all of these parameters simultaneously, although desirable, would present almost insurmountable technical difficulties in a controlled study. Therefore, an attempt has been made to reduce the number of experimental variables to realistic proportions. This has been done in part by examining the effect of acclimatization in two separate experiments. We have attempted to remove differences in metabolic heat production by limiting ourselves to a single (theoretical) work rate. This leaves us with the interplay of environment and uniform as independent variables on some specified physiologic (temperature, sweat rates, tolerance times) dependent variable. Thus we are left with a bifactorial experiment (environmental factors and uniform factors). The environment itself is a combination of many things: temperature (dry bulb), water content, radiant temperature, and wind movements. Many indices have been developed to relate on a single scale the "stress" of the composite environment to the "strain" it produces in the human organism. The index most widely used by the military and the one used here is the WBGT of Yaglou and Minard.[6]

In experiments of this kind, particularly in the military, one will lose subjects for medical or administrative reasons. Because a factorial analysis of variance for uneven numbers of within cell observations was not feasible at the time, cell sample size has been equalized. To reduce the bias that this dropping of observations may introduce, if data were incomplete on a subject, we eliminated the data across the whole range of test environment. This results in a reduction in sample size from the theoretical 24 to as low as 18 in some cases.

A further complication is that many of the variables we are interested in observing (such as Tr, ΔTr, $\overline{Ts}$, etc.) can be measured at any time during the course of the experiment, and although all of our temperature data are taken once a minute, we calculate derived temperature such as $\overline{Ts}$ and Tb every 5 minutes. Little is to be gained by grouping and analyzing the data for each

5-minute period; therefore, four test times were chosen to analyze the data: 0, 25, 45, and 90 minutes were chosen to give a maximum number of readings for each environment.

As the stress of the environment increases, men are progressively less able to tolerate it. Thus at 0 and 25 minutes we have sufficient numbers of subjects from all groups to study, but at 45 minutes so few subjects remain at the most severe environment (95.9 WBGT) that this environment is dropped from the analysis. Likewise, at 90 minutes insufficient numbers of subjects in the 89° WBGT environment remain to warrant this inclusion.

Rectal Temperature

The object of all of these experiments is to be able to predict how long men can be expected to tolerate a given environment and to determine the extent to which this tolerance is significantly changed by wearing body armor. To fulfill this requirement, it is necessary to study some indicator of increasing physiologic strain such as the rise in rectal temperature that occurs during the course of the experiment. As indicated in the General Results section, analysis of the grouped data on rectal temperatures at any particular time becomes difficult because of differences in the starting rectal temperature. We have used two different methods to overcome this source of variation. One method of doing so is to consider delta values (or the rise in rectal temperature from time 0). We can analyze these delta values (ΔTr) for the effects of environment and body armor, independent of difference in starting rectal temperature.

The other method we have used is to analyze grouped rectal temperatures as the variable in an analysis of covariance with starting rectal temperature (Tr_0) as the covariate. This procedure thus removes the effect that pre-exposure of the men has on the base line rectal temperature. This removes variation in Tr_0 and partitions the adjusted variance of Tr at the desired time into temperature and body armor effects. It also provides the basis for adjusting calculated mean values and permits testing these adjusted means for significant differences. The use of covariance for analyzing rectal temperature is justified physiologically because rectal temperature (as opposed to skin temperature) is homeostatically restricted to a fairly narrow range by the body defense mechanisms. As a result of this statistical treatment, the data are a better approximation of the expected response in a large population not subjected to the changes caused by the short pre-exposure.

We can examine the analysis of variance performed on the unadjusted Tr data in Parts A, B, C and D of Table 7. It is pertinent to note that in the analysis of the data for Tr_0 there is a highly significant temperature effect

Table 7

Analysis of Variance of Rectal Temperature

Time (min)	Source	df	SS	MS	F Ratio
(Part A) 0	Environment	2	1.5650	0.7825	9.5310**
	Body Armor	1	0.0012		<1
	Temp x BA	2	0.5453	0.2726	3.3203*
	Error	102	8.3833	0.0821	
(Part B) 25	Environment	2	20.3444	10.1722	84.5596**
	Body Armor	1	0.2167		1.8013
	Temp x BA	2	0.0000		<1
	Error	102	12.2726	0.1203	
(Part C) 45	Environment	1	6.9688		52.6742**
	Body Armor	1	0.2567		1.9402
	Temp x BA	1	0.0272		<1
	Error	68	9.0023	0.1323	
(Part D) 90	Body Armor	1	0.5500		3.2953
	Error	34	5.6778	0.1669	

* Significant at .05 level

** Significant at .01 level

($p<.01$) and a significant interaction ($p<.05$) between temperature and body armor, but there is no significant body armor effect. Parts B and C of Table 7 reveal a highly significant effect of environment on the rectal temperature, which is to be expected. In the unadjusted data on rectal temperature, there is no significant effect that can be attributed to body armor at any temperature.

Because of the significant interaction in the analysis of the 0 time data, it is of interest to examine the simple effects of body armor within each temperature level. This is done in Table 8. We see that the significant interaction is due to the effect of body armor at 95.9° WBGT, and that body armor does not appear to have an effect on resting rectal temperature at the other two environments.

The analysis of covariance of the data at 25, 45, and 90 minutes is presented in Tables 9, 10, and 11.

The F ratios derived from these analyses are collected in Table 12. Unadjusted refers to the routine analysis of variance, and adjusted refers to the analysis of covariance.

Table 8

Simple Effects of Body Armor Within Each Temperature Level
Tr at Time Zero

Source	df	SS	MS	F Ratio
Body Armor (within 82.4°F)	1		.0434027	<1
Body Armor (within 89.0°F)	1		.0756250	1.1475
Body Armor (within 95.9°F)	1		.2934027	4.452*
Error	90	5.93132	.0651793	

*Significant at .05 level

Table 9

Analysis of Covariance Tr_{25} versus Tr_0

		Sum of Products			Tr25 Adjusted for Tr_0			
Source	df	x^2	xy	y^2	df	SS	MS	F Ratio
Total	107	10.3606	12.4932	34.5323				
Replicates	17	2.4519	2.3982	4.9844				
Treatments	5	1.9774	5.1454	21.9338				
Environment	2	1.5650	4.9900	21.8204				
Body Armor	1	.0011	.0070	.0428				
Environ. x BA	2	.4113	.1484	.0706				
Error	90	5.9313	4.9496	7.6141	89	3.4837	.03914	
Environ. + E	92	7.4963	9.9396	29.4345	91	16.2553		
Environment effect adjusted for Tr_0					2	12.7716	6.3053	163.15**
Body Armor + E	91	5.9325	4.9566	7.6569	90	3.5157		
Body Armor effect adjusted for Tr_0					1	.0320	.0320	.816
Environ. x BA + E	92	6.3427	5.0980	7.6848	91	3.5872		
Environ.-BA interaction adjusted for Tr_0					2	.1033	.0517	1.3201

** Significant at .01 level

Table 10

Analysis of Covariance Tr_{45} versus Tr_0

Source	df	Sum of Products			Tr_{45} Adjusted for Tr_0			
		x^2	xy	y^2	df	SS	MS	F Ratio
Total	71	6.1549	2.5984	17.4616				
Replicates	17	3.0436	1.8753	4.9373				
Treatments	3	0.3390	-1.1677	7.6787				
Environment	1	0.1422	-1.0200	7.3153				
Body Armor	1	0.1800	-0.1975	.2167				
Environ. x BA	1	0.0168	.0498	.1467				
Error	51	2.27722	1.8508	4.8457	50	3.5560	.0711	
Environ. + E	52	2.9145	.8708	12.1610	51	11.9008		
Environment effect adjusted for Tr_0					1	8.3448		117.35**
Body Armor + E	52	2.9522	1.69334	5.0624	51	4.0911		
Body Armor effect adjusted for Tr_0					1	0.53511		7.525**
Environ. x BA + E	52	2.7890	1.5406	4.9924	51	3.6421		
Environ.-BA interaction adjusted for Tr_0					1	.0861		1.2104

**Significant at .01 level

Table 11

Analysis of Covariance of Tr_{90} versus Tr_0

Source	df	Sum of Products						
		x^2	xy	y^2	df	SS	MS	F Ratio
Total	35	3.4547	1.6038	6.1119				
Replicates	17	2.1772	0.7800	2.5806				
Body Armor	1	.0400	-0.1783	0.7951				
Error	17	1.2375	1.0021	2.7361	16	1.9247	0.1203	
BA + E	18	1.2775	.8238	3.53125	17	3.0001		
Body Armor adjusted for Tr_0					1	1.07536		8.9357

Table 12

F Table

Time (min)	Environment		Body Armor		Environ. x BA	
	Unadjusted	Adjusted	Unadjusted	Adjusted	Unadjusted	Adjusted
0	9.531**	-	<1	-	3.320*	-
25	84.6 **	163.1**	1.801	<1	<1	1.320
45	52.7 **	117.4**	1.940	7.525*	<1	1.2104
90	-	-	3.295	8.9357**	-	-

* Significant at .05 level

** Significant at .01 level

We can see that there is a highly significant effect due to the differences in environment in both the adjusted and unadjusted sets of data. We also see that at 45 and 90 minutes the analysis of covariance reveals a significant effect of body armor. Analysis of covariance of the data at 25 minutes does not reveal a significant body armor effect. This is probably explained by the fact that at 25 minutes, particularly at the less stressful environments, insufficient amounts of sweat have been produced and evaporated to make the block imposed by body armor important.

In addition, the significant effect of body armor on Tr_0 at the 95.9°F environment is included in this analysis at 25 minutes in opposition to the assumption that the independent covariate should be unaffected by treatment effects. The data in Table 12 reveal the usefulness of using an analysis of covariance to adjust the data, as meaningful effects of body armor found at 45 and 90 minutes would have been overlooked in the routine analysis of variance. The fact that effects of environment are appreciable even without removing the differences due to starting rectal temperature, but that body armor effects are not, indicates the relative degree of stress of the environment and the body armor, a concept referred to in the General Results section.

The data on mean values in Table 1 at times 25, 45, and 60 minutes are the means adjusted by the analysis of covariance presented here. Examination of the unadjusted treatment means for differences due to body armor fails to reveal any that are significant.

The analyses of variance of the data on ΔTr are presented in Table 13. As before, there is a highly significant effect due to environment at both 25 and 45 minutes. No environmental effect is noted at 90 minutes because only one environment (82.4° WBGT) is represented.

Table 13

Analysis of Variance of Delta Rectal Temperature

Time (min)	Source	df	SS	MS	F Ratio
(Part A) 25	Environment	2	14.6008333	7.3004165	115.4 **
	Body Armor	1	.2750877	.2750877	4.349*
	Temp. x BA	2	.0010859	.0005429	ns
	Error	108	6.8316125	.0632556	
(Part B) 45	Environment	1	9.9429	-	84.5 **
	Body Armor	1	1.0736	-	9.125**
	Temp. x BA	1	.0400	-	<1
	Error	84	9.8834	.1177	
(Part C) 90	Body Armor	1	2.7106	2.7106	16.453**
	Error	40	6.5899	1647	

* Significant at .05 level.

** Significant at .01 level

Unlike the Tr per se (adjusted by covariance), there is a significant ΔTr effect due to body armor at 25 minutes as well as at 45 and 90 minutes. However, if one examines the individual treatment means at 25 minutes for differences due to body armor, we see in Table 14 that none of the means with armor are significantly different from their corresponding mean without armor; at 45 minutes the effect of body armor is significant at the 82.4°WBGT environment but not at the 89° environment.

The graphs of treatment mean effects in the General Results section were not meant to imply a continuum. In attempting to predict tolerance times, we would like to know the regression of rise in rectal temperature as a function of time. To do this, we have pooled all available 5-minute observations up to 60 minutes for a given environment and uniform condition. Of the six regressions (three temperatures times two armor conditions) thus defined, we have compared the regression with armor against the regression without armor at each of the three environments by testing the pooled residual error mean squares.[11] The analyses of variance of these six lines are presented in Table 15, Parts A, B, C. The two regressions of ΔTr versus t at 82.4°F WBGT are highly significantly different (F = 47.5**). These two lines and their regression equations are presented in Figure 8. The two regressions at 89° are also significantly different (F = 52.0**). These two lines and their regression equations

**Significant at .01 level

Table 14

Delta Rectal Temperature Treatment Means

Time (min)	Armor	Temperature (°F)		
		82.4	89.0	95.9
25	Without	.461	.753	1.329
	With	.563	.855	1.418
45	Without	.759	1.474	
	With	1.023*	1.652	
90	Without	.950		
	With	1.461*		

*Denotes significant difference between the two means tested by <u>lsd</u> (.05)

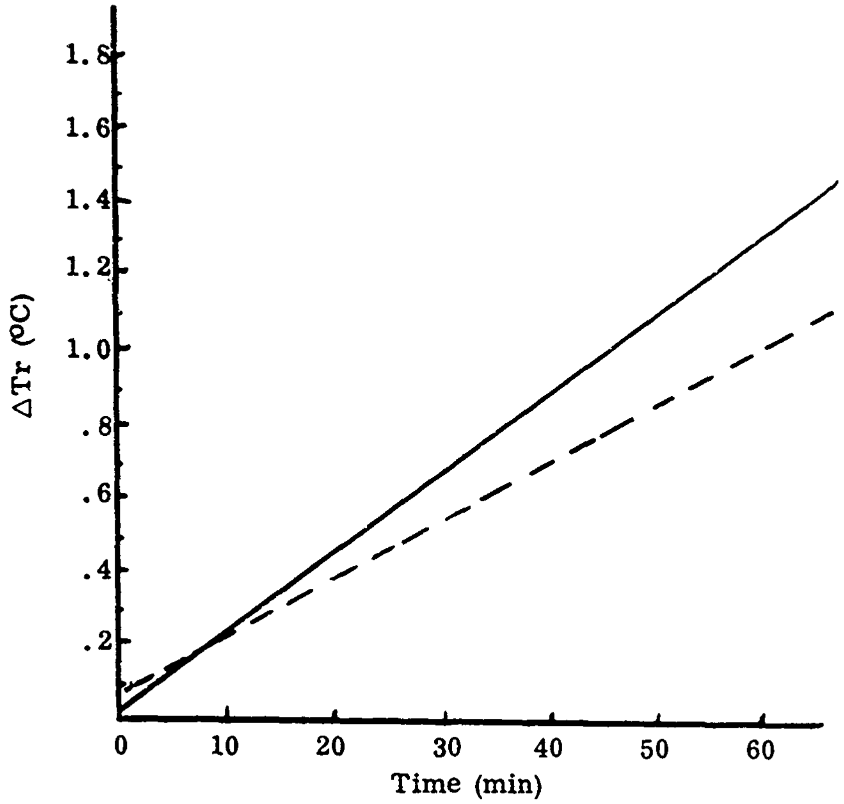
Table 15

Analysis of Variance of Regression of ΔTr (x10) Versus t

WBGT (°F)	Armor	df	Σx^2	Σxy	Σy^2	Reduction	Residual		
							SS	MS	F
(Part A) 82.4	Without	289	103050.69	16238.03	3800.55	2557.49	1243.06	4.301	594**
	With	295	100124.92	22021.48	6508.87	4842.52	1666.35	5.649	857**
(Part B) 89.0	Without	290	105350.59	33027.42	12605.92	10354.09	2251.82	7.765	1333**
	With	280	81333.40	32000.99	12779.66	12589.19	190.47	0.680	18508**
(Part C) 95.9	Without	185	32329.10	16914.96	10063.11	8849.91	1213.21	6.558	1349**
	With	164	16469.61	10858.22	7207.69	7157.74	49.95	0.305	23506**

**Significant at .01 level

Fig. 8. Rise of Rectal Temperature as a Function of Time at WBGT 82.4°F



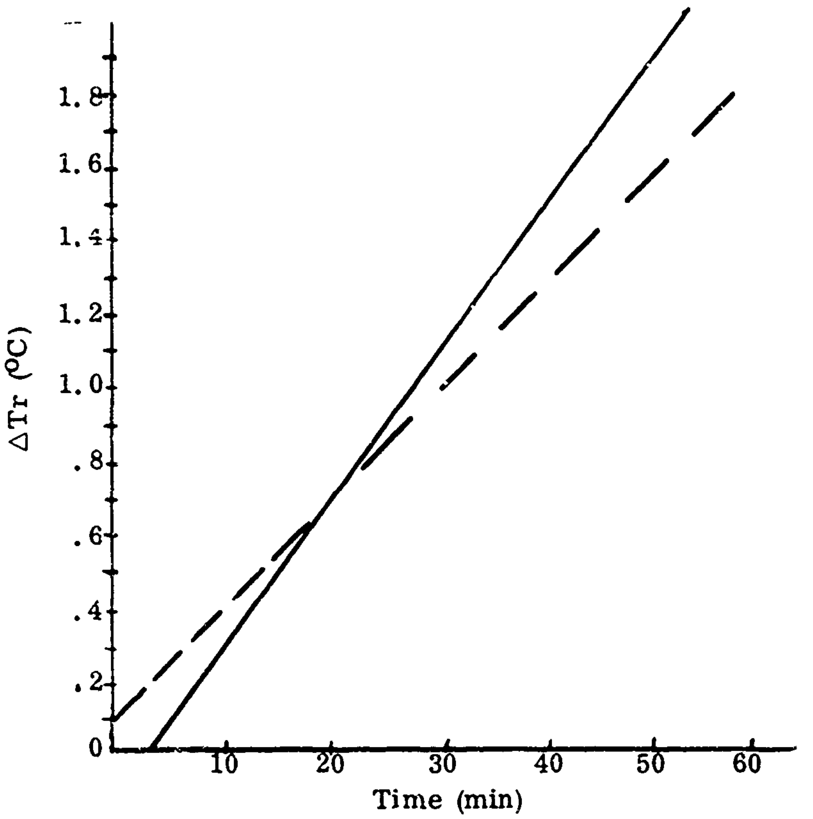
—— With armor $\Delta Tr = 0.02199t + 0.0002$

– – – Without armor $\Delta Tr = 0.01575t + 0.04908$

are presented in Figure 8. The two regressions at 89° are also significantly different ($F = 52.0^{**}$). These two lines and their regression equations are presented in Figure 9. The highly significant difference in the two lines is probably attributable in large part to the exceedingly small error variance in the regression with armor (0.68, Table 15B). In a similar manner the two regressions at 95.9°F WBGT were tested and found to be significantly different ($F = 33.4^{**}$). These lines and their regression equations are shown in Figure 10. At this condition, the regression with armor has an extremely small error variance (.305, Table 15C). Thus at all three environments the regression of the data from men with armor differs from those without armor.

** Significant at .01 level

Fig. ^. Rise of Rectal Temperature as a Function of Time at WBGT 89.0°F



Therefore, all the data with armor were combined in a multivariate analysis with WBGT as a second independent variable. The data without armor were similarly pooled. This allows us to define two regressions, the expected tolerance time as a function of acceptable rise in ΔTr and environment in men wearing armor and in those not wearing armor.

Expected tolerance time in men with utilities only:

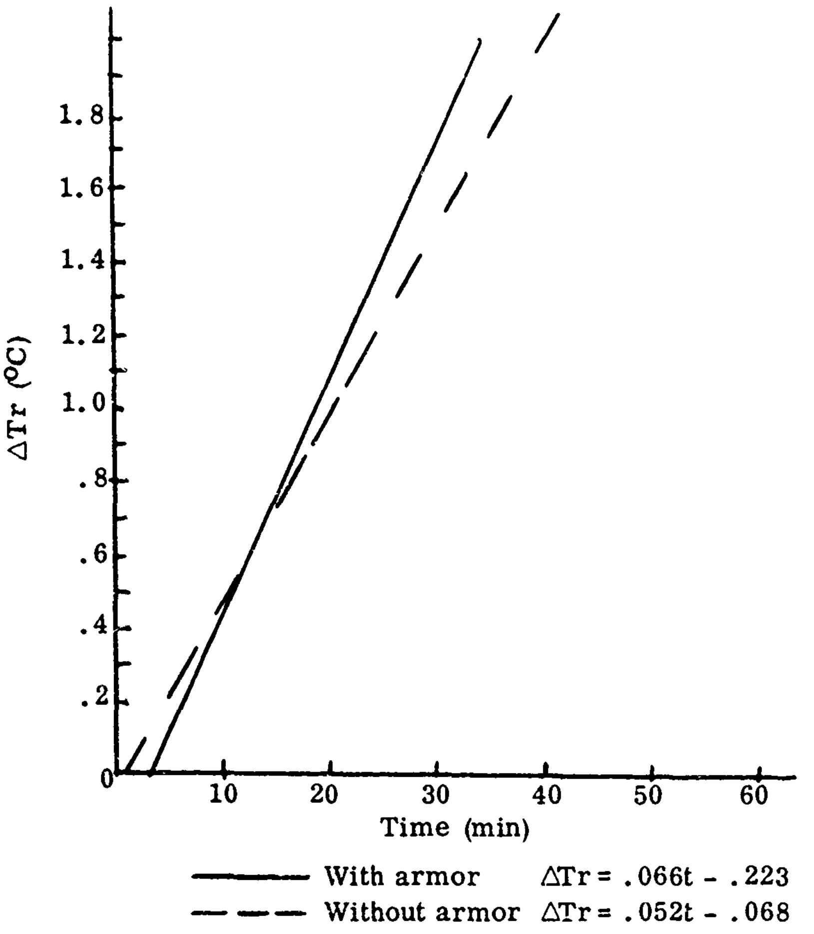
$$Tt = 142.05 + 25.04 \text{ final } \Delta Tr - 1.5227 \text{ WBGT} \qquad \text{(Equation 1)}$$

Expected tolerance time in men with utilities and body armor:

$$Tt = 122.79 + 24.34 \ \Delta Tr \text{ final} - 1.324 \text{ WBGT} \qquad \text{(Equation 2)}$$

These two equations are a preliminary attempt to define tolerance time as a function of environment and uniform. They may be useful for times

Fig. 10. Rise in Rectal Temperature as a Function of Time at WBGT 95.9°F



up to 60 minutes. The rise of rectal temperature as a function of time is well approximated by a linear regression, which can be confirmed by comparing the calculated ΔTr of each of the six regression equations. These two equations (Equations 1 and 2) tend slightly to overestimate tolerance time at the more stressful environments, suggesting that effect of environment is not linear and that further analysis will be required to achieve a better model.

Skin Temperature

In analyzing the data on skin temperature, we might ask whether it is justifiable to analyze this data in a manner similar to that employed with rectal temperature; that is, to analyze effects on skin temperature after removing differences in base line starting temperatures. The analysis of variance of mean

skin temperatures at time 0 (Table 16A), we see that there are highly significant effects attributable to both environment and body armor. In addition, Table 2 shows that there are significant effects due to body armor at all three environments at time 0. It seems that this high level of treatment effects makes an analysis of covariance with $\overline{Ts}_0$ as the independent covariate impracticable. With rectal temperatures, only after the data of Tr_0 at 95.9^{o} (where there was the only significant body armor effect) were removed did the subsequent analysis of covariance at times 45 and 90 yield significant differences due to body armor. More important than this statistical reasoning, eliminating differences in starting skin temperatures cannot be justified physiologically.

Table 16

Analysis of Variance of Mean Skin Temperature ($\overline{Ts}$)

Time (min)	Source	df	SS	MS	F Ratio
(Part A)	Environment	2	47.6857	23.8428	110.6 **
0	Body Armor	1	5.3778		24.943**
	Environ. x BA	2	.1027	.0513	<1
	Error	102	21.9985	0.2156	
(Part B)	Environment	2	128.9386	64.4693	307.0 **
25	Body Armor	1	6.0207		28.67 **
	Environ. x BA	2	.8510	.4255	2.026
	Error	102	21.4219	0.2100	
(Part C)	Environment	1	24.3835		55.7 **
45	Body Armor	1	6.3013		14.40 **
	Environ. x BA	1	.0007		<1
	Error	68	29.7573	0.4376	
(Part D)	Body Armor	1	4.7518		11.90 **
90	Error	34	13.5745	0.3992	

** Significant at .01 level

Unlike rectal or core temperature, skin temperature is not maintained within a narrow range, but changes markedly in response to environment (or at least microenvironment). The data of Table 17 show a highly significant environmental effect at all temperatures tested; body armor also produces highly significant effects at all times. This confirms the significant differences shown in Table 2.

The effects of environment and body armor after the elimination of initial starting differences can be interpreted by studying data on $\Delta\overline{T}s$. The analyses of variance are presented in Table 17 and the means in Table 18. They reveal the expected environmental effect. However, body armor produces a significant effect only at 90 minutes, when a single environment is represented. Comparing these data with those of Table 16 suggests that effects due to body armor, at least in these environments, are exerted in the resting state; working further increases the skin temperature but does not change the magnitude of the difference due to armor.

Table 17

Change in Skin Temperature (ΔTs) (^{o}C)

Time (min)	Source	df	SS	MS	F Ratio
(Part A) 25	Environment	2	15.9755	7.9877	31.6 **
	Body Armor	1	.0088		<1
	Environ. x BA	2	.3635	.1818	<1
	Error	102	25.6419	.2513	
(Part B) 45	Environment	1	14.1600		38.42 **
	Body Armor	1	.8201		2.24
	Environ. x BA	1	.1412		<1
	Error	84	30.9661	.3686	
(Part C) 90	Body Armor	1	1.9741	1.9741	5.465*
	Error	40	14.4511	.3612	

* Significant at .05 level

** Significant at .01 level

Table 18

Average Rise in Mean Skin Temperature ($\Delta \bar{T}s$) (^{o}C)

Time (min)	Armor	WBGT Levels 82.4°F	89.0°F	95.9°F	lsd (.05)
25	Without	.950	1.556	1.878	.330
	With	1.028	1.400	1.983	
45	Without	1.100	1.982		.364
	With	1.373	2.095		
90	Without	1.02			.375
	With	1.46*			

*Significant at .05 level.

Mean Body Temperature ($\bar{T}b$) and Heat Storage

Physiologically, mean body temperature is somewhat intermediate between rectal and skin temperature in terms of homeostatic limitations. The analysis of variance of the data on mean body temperature at time 0 is presented in Part A of Table 19, and shows that both environment and armor produce significant effects. At all other times (Parts B, C, and D of Table 19), the effect of body armor is highly significant.

To study the effects of environment and armor independent of differences in starting body temperature, we have analyzed the data on ΔTb (calculated from time 0). The data, presented in Tables 20 and 21, show that there is no body armor effect at 25 minutes but that there is a highly significant effect of body armor at 45 and 90 minutes. Examination of the treatment means in Table 21 shows that this is due to the differences imposed by armor at the 82.4°F environment alone.

The data on heat storage (ΔS) are essentially the same as the ΔTb, but include differences due to size of the men (see Tables 22 and 23). These reveal that ΔS, like ΔTb, is only significant at 45 and 90 minutes in the 82.4°F environment.

Sweat Rate

The analysis of variance of the total sweat production rate (TSP) and the efficiency of sweat evaporation are presented in Tables 24 and 25. The

Table 19

Analysis of Variance - Mean Body Temperature ($\overline{T}b$)

Time (min)	Source	df	SS	MS	F Ratio
(Part A) 0	Environment	2	9.9924	4.9962	54.7228**
	Body Armor	1	.4156		4.552 *
	Environ. x BA	2	.2186	.1093	1.1971
	Error	102	9.3189	.0913	
(Part B) 25	Environment	2	47.7906	23.8953	196.3 **
	Body Armor	1	1.2893		10.59 **
	Environ. x BA	2	.0006	.0003	<1
	Error	102	12.4161	.1217	
(Part C) 45	Environment	1	14.9645		88.4 **
	Body Armor	1	1.8605		10.99 **
	Environ. x BA	1	.1620		<1
	Error	76	12.8650	.1692	
(Part D) 90	Body Armor	1	2.681		11.91 **
	Error	34	7.6535	.2251	

* Significant at .05 level

** Significant at .01 level

Table 20

Analysis of Variance Rise in Mean Body Temperature ($\Delta\overline{T}b$)

Time (min)	Source	df	SS	MS	F Ratio
(Part A) 25	Environment	2	14.5239	7.2619	114.9 **
	Body Armor	1	.1337		1.788
	Environ. x BA	2	.2493	.1246	1.977
	Error	102	6.4501	.0632	
(Part B) 45	Environment	1	11.3474		74.5 **
	Body Armor	1	.7642		5.02 **
	Environ. x BA	1	.0927		<1
	Error	84	12.8013	.1523	
(Part C) 90	Body Armor	1	1.524		7.693**
	Error	40	7.9254	.1981	

**Significant at .01 level

Table 21

Average Rise in Mean Body Temperature ($\Delta\bar{T}b$)

Time (min)	Armor	WBGT Levels			lsd (.05)
		82.4°F	89.0°F	95.9°F	
25	Without	.600	1.089	1.522	.166
	With	.739	1.072	1.611	
45	Without	.859	1.641		.234
	With	1.109*	1.764		
90	Without	1.038			.278
	With	1.419*			

*Significant at .05 level

Table 22

Analysis of Variance of Heat Storage (ΔS)

Time (min)	Source	df	SS	MS	F Ratio
(Part A) 25	Environment	2	42331.14	21165.57	89.81 **
	Body Armor	1	535.16		2.27
	Environ. x BA	2	105.99	54.99	<1
	Error	102	24038.24	235.67	
(Part B) 45	Environment	1	31445.82		59.27 **
	Body Armor	1	3506.80		6.61 *
	Environ. x BA	1	137.81		<1
	Error	84	44562.62	530.51	
(Part C) 90	Body Armor	1	7051.13		9.036**
	Error	40	31212.40	780.31	

* Significant at .05 level

** Significant at .01 level

Table 23

Mean Heat Storage ($\Delta\bar{S}$)

Time (min)	Armor	Environmental WBGT 82.4°F	89.0°F	95.9°F	lsd (.05)
25	Without	45.76	62.81	92.39	10.13
	With	38.52	61.20	88.37	
45	Without	53.65*	93.17		13.89
	With	68.12	104.21		
90	Without	60.65*			17.41
	With	86.57			

*Significant at .05 level

Table 24

Analysis of Variance of Sweat Rate Per Hour

Source	df	SS	MS	F Ratio
Environment	2	69.6387	34.8193	73.3 **
Body Armor	1	1.8451		3.884
Environ. x BA	2	0.7132	0.3566	<1
Error	114	54.1533	.4750	

**Significant at .01 level

Table 25

Analysis of Variance of TSE/TSP x 100

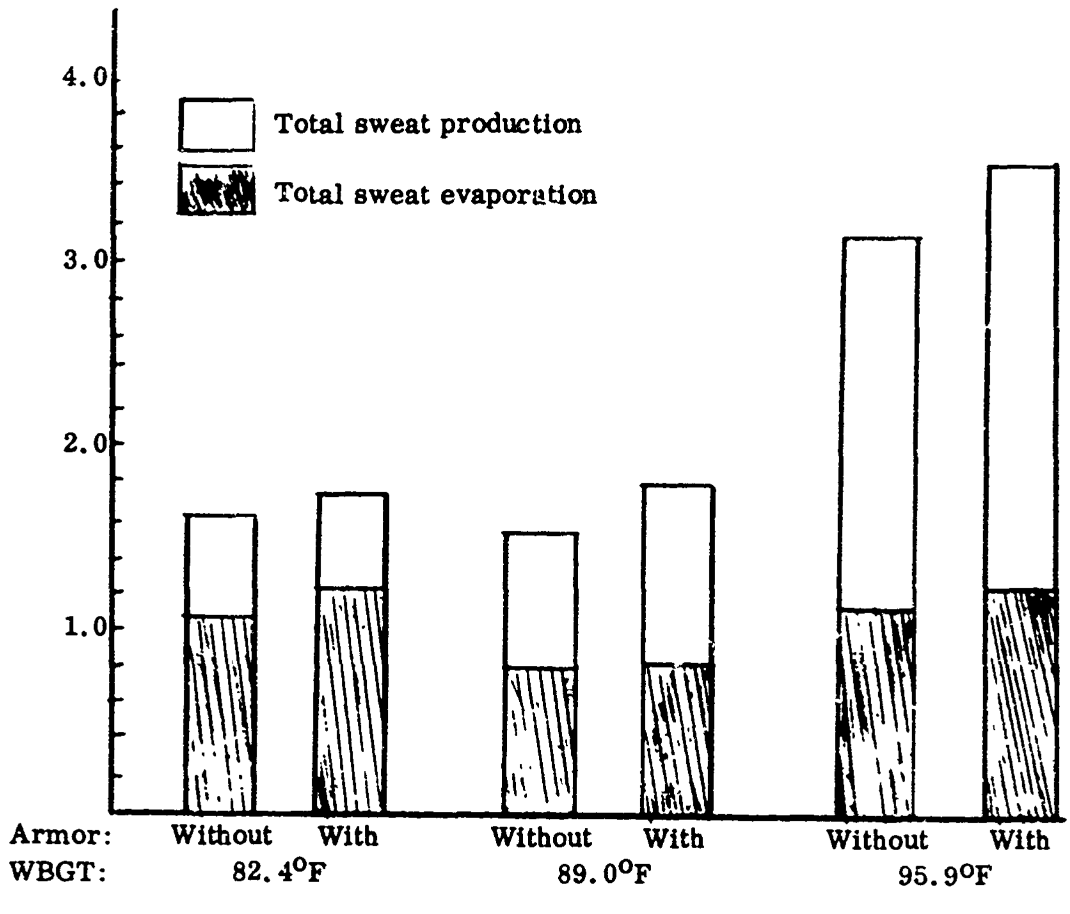
Source	df	SS	MS	F Ratio
Environment	2	1.1981	0.5990	35.87 **
Body Armor	1	0.0916		5.485*
Environ. x BA	2	0.0135	0.0067	<1
Error	114	1.9063	0.0167	

* Significant at .05 level

** Significant at .01 level

means of sweat production rate (Table 4) and the mean efficiency of sweat evaporation (Table 5) are combined in Figure 11. This suggests that, at least under the condition of this experiment, the level of stress seems to be related more to total sweat production rather than total sweat evaporation. The amount of sweat evaporated (roughly, 1 liter per hour) would provide approximately 600 kcal of cooling each hour, a figure which is commensurate with the work rate. Comparing the effects of environment and body armor on total sweat production, we find, particularly at 95.9°F WBGT, that the environmental stress is relatively greater than the armor stress. Again, caution must be expressed in too strict a comparison due to the effect that time in the chamber makes on the factor of sweat evaporation. Thus, these data confirm the physiologic tenet that the body attempts to evaporate an amount of sweat which will remove its metabolic heat, and shows that if the efficiency of evaporation drops, either due to the environment or to the presence of body armor, the body responds by increasing the sweat rate.

Fig. 11. Sweat Evaporation and Sweat Production (liter/hr)



Metabolic Rate

A factorial analysis of variance of the metabolic rate was not done because of the fact that the number of observations per cell differed greatly. All of the metabolic rate data were considered to represent 16 different treatments (3 temperatures x 3 times x 2 armor conditions minus 2 for no observations from 70 to 80 minutes at the 95.9°F environment in either armor condition), and analyzed by a straight analysis of variance for differing numbers of N. The cell means were then tested by Kramer's extention of Duncan's test.[12] ..s combined analysis of variance is presented in Table 26. No significance was detected using the error mean square thus provided, but because the treatment effects in Figure 5 suggested a possible effect of temperature on metabolic rate, the data from 10-20 minutes for the three temperatures were considered separately. These data are presented in Table 27 and Figure 12. They show that there is a highly significant temperature effect. Unlike the effect of cold on changing metabolic rate,[13] we feel that the effect is due to the earlier onset of fatigue at very stressful environment and only represents the well-known fatigue effect.[14]

Table 26

Analysis of Variance of Metabolic Rate

Source	df	SS	MS	F Ratio
Treatments	15	9.9248	0.6616	<.6833
Error	266	257.5490	0.9682	

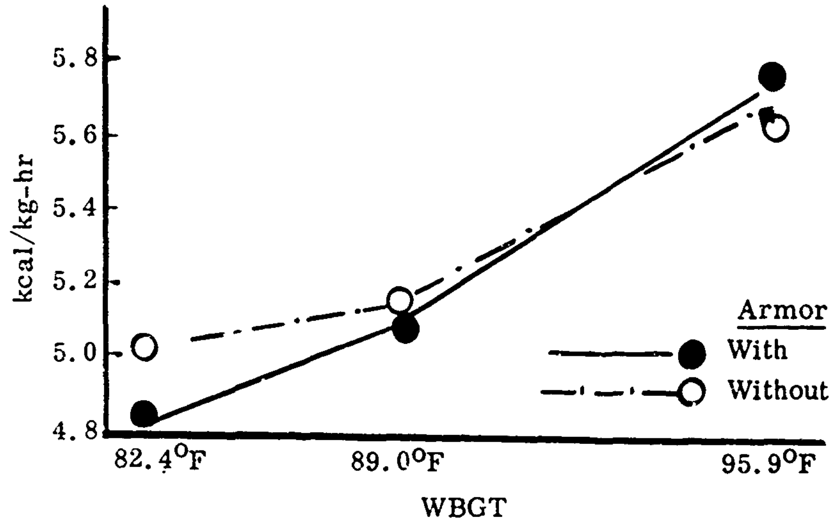
Table 27

Analysis of Variance of Metabolic Rate (Time 10-20 Minutes)

Source	df	SS	MS	F Ratio
Environment	2	11.9637	5.9818	6.501**
Body Armor	1	.1501		< 1
Environ. x BA	2	.1640	.0820	< 1
Error	96	88.3352	.9201	

**Significant at .01 level

Fig. 12. Metabolic Rate in Initial 30 Minutes



Heat Loss

The data on heat loss are presented graphically in the histogram of Figure 13. Due to the variation in number of observations (the number in parentheses above each bar) and the inherent variability of metabolic data, the only data that are significantly different due to the presence of armor are those in the 60 to 90-minute sample at 89°F. Figure 13 suggests that heat loss increases as a function of time, which is expected due to the lag between onset of sweating and effective cooling from sweat evaporation. It also shows the fall in heat loss as a function of armor and increasing environmental stress.

Anthropometric Data

Data relating to the size and shape of our subject population and to the relation of the chest and abdominal size to the fit of their armor are presented in Table 28. The data on mean rise in rectal temperature were adjusted by analysis of covariance using differences in armor fit (armor gap at the lower thorax) to see if this significantly changes the means. No significant change in means or F ratios occurs but the armor gap was fairly uniform. It is possible that marked differences in armor gap might be important in the thermal effect of body armor.[4]

Fig. 13. Heat Lost (kcal/hr)

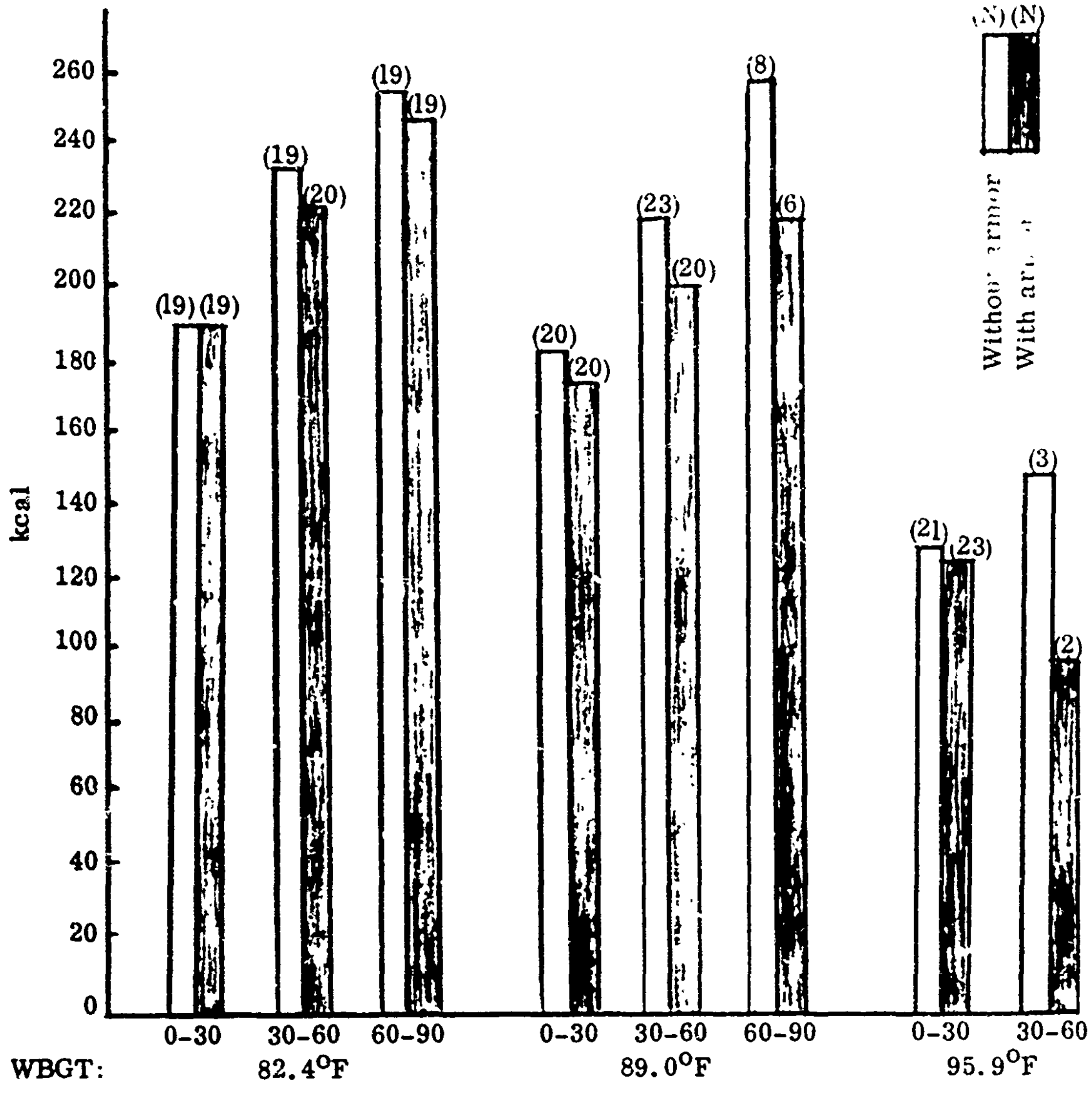


Table 28

Anthropometric Data

Attribute	Mean	SEM
Height (cm)	175.0	1.10
Weight (kg)	70.852	1.49
Body Surface Area (m^2)	1.849	0.023
Chest Relaxed (cm)	89.0	0.77
Chest Expanded (cm)	92.7	0.71
Waist (cm)	77.5	0.97
Armor Gap (cm)	6.95	0.45

CONCLUSIONS

1. The rectal temperatures of men wearing personnel body armor are significantly higher than those of men not wearing armor in environments of 82.4°F WBGT (current study) and 87.3°F WBGT (previous study).

2. Although the rectal temperature is generally higher in the men wearing armor at 89°F and 95.9°F WBGT, it is not significant in most cases.

3. The data on rectal temperature reveal that the most significant effect of body armor in elevating rectal temperature is felt at environments whose WBGT is less than 88°F.

4. In the 80-88°F WBGT level of environmental stress, comparison of the rise in rectal temperature reveals that wearing body armor produces an effect roughly equivalent to a 5° rise in the WBGT for unarmored men.

5. At higher levels (WBGT 89°F and 95.9°F WBGT), the stress of the environment is so great that little additional increase in rectal temperature can be attributed to body armor.

6. Because all men lasted the full 90 minutes, both with and without armor at 82.4°F WBGT, no tolerance time could be determined. Due to the marked differences in the rise in rectal temperature, it is expected that during the course of a real work day, men with armor would show progressively higher rectal temperatures and would eventually become heat casualties before men without armor in environments in the range of 82-88°F WBGT.

7. Pre-exposing the men to cause skin temperature equilibrium produced changes in core temperature. It is unlikely that similar differences would occur if the subjects had actually been living in these environments for some time. The prime factor in changing core temperature was the environment, but body armor did exert a significant effect in the 95.9°F WBGT environment.

8. Analysis of pooled data for the regression of ΔTr versus time indicates that, within each environment, the regression with armor is significantly different from the regression without armor.

9. Both environment and body armor significantly elevate the mean skin temperature.

10. At WBGT equal to 82.4°F, skin temperature comes into equilibrium with the environment around 50 minutes; at 89°F and 95.9°F, it continued to rise as long as men were in the chamber.

11. Skin temperature, like rectal temperature, shows that the magnitude of the body armor effect decreases with increasing environmental stress.

12. Under the conditions of our experiment, the effect of the presence of body armor on mean skin temperature is exerted in the initial equilibration period. During work, skin temperatures continue to rise but no further significant change in the magnitude of the body armor effect occurs.

13. Environment creates significant changes in base line mean body temperatures, due primarily to the difference of resting skin temperatures.

14. The major differences seen in mean body temperature due to the presence of armor are confined to the least stressful environment.

15. Comparison of mean body temperature and heat storage data reveals that at the more stressful environments not only are differences in armor less important, but also that differences in body surface area are less effective in heat dissipation.

16. Analyses of sweat rate and sweat evaporation suggest that the body attempts to maintain a rate of sweat evaporation which is commensurate with the metabolic rate.

17. The combined stress of increasing amounts of water vapor in the environment and decreased evaporative ability due to body armor is reflected in a heightened rate of sweat production coupled with a fall in percentage of sweat evaporation.

18. Comparison of total sweat production rates confirms other information that environment rather than body armor represents the more significant stress at 95.9°F WBGT.

19. When the men wore body armor, their efficiency for evaporative cooling decreased. This was reflected in a drop in the percentage of their total sweat which was evaporated. This, the primary factor whereby body armor produces its effects on skin, rectal and body temperatures, was seen in all test environments but was statistically significant only at 82.4°F WBGT.

20. Tolerance times could be defined for the 89 and 95.9°F WBGT environments. These were: 89°F without armor, 71.3 minutes; 89°F with armor, 63 minutes; 95.9°F without armor, 32.3 minutes; and 95.9°F with armor, 28.4 minutes.

21. Generally speaking, our assumption of a uniform metabolic rate related to load grade and speed is validated.

22. In consideration of the metabolic data from times 10 to 20 minutes only, it would appear that there is an increase in metabolic rate as a function of increasing environmental temperatures, but this probably represents only an earlier onset of fatigue.

23. Generally speaking, the heat loss is greater in the subjects not wearing armor, but this is statistically significant only in the 89°F environment during the 30-60 minute time period.

24. Physiologic strain in man is the result of the summation of stresses that operate upon him. In this and our previous study, the combination of stresses is such that at lower WBGT (32.4 and 87.3°F) armor represents the more significant stress, whereas at higher WBGT it is the environment which is the major stress and armor is relatively unimportant.

25. The data confirm the importance of the 88°F WBGT suggested by Yaglou and Minard) as a point where the body's capabilities to deal with increasing environmental stress begin to break down.

26. It appears that there is a zone (roughly WBGT 80-88°F) where body armor can be expected to decrease working time. At the lower end, evaporative and non-evaporative cooling is so efficient that enough heat can be removed from unoccluded areas to make the presence of body armor insignificant. (In fact, in areas with high radiant intensity but low humidity, body armor may be beneficial by acting as a solar screen.[15]) At the higher levels, evaporative cooling is relatively inefficient, and tolerance times so short that further blocking of evaporation by body armor is relatively meaningless.

REFERENCES

1. Yarger, W. E., L. H. Cronau, Jr., and R. F. Goldman. Body Armor in a Hot Humid Environment. Part 1: Studies in Unacclimatized Men. Naval Medical Field Research Laboratory report, Vol. 18, No. 16, September 1968.

2. Airborne Instruments Laboratory Division of Cutler-Hammer, Deer Park, Long Island, N. Y. "Type 440 Multichannel Skin Temperature Programmer," Report No. 5991-H-1, February 1960.

3. Burton, A. C. A New Technique for the Measurement of Average Skin Temperature Over Areas of the Body. J. Nutrition, 7:481, 1934.

4. Yarger, W. E. and R. F. Goldman. Unpublished data, January 1968.

5. Weir, J. B. De V. New Method for Calculating Metabolic Rate with Special Reference to Protein Metabolism. J. Physiol. 109:1, 1949.

6. Yaglou, C. P. and D. Minard. Prevention of Heat Casualties at Marine Corps Training Centers. Harvard College, Boston (ONR Contract N5ori-07665), May 1956.

7. Goldman, R. F. In press, Mil. Med.

8. Steel, R.G.D. and J. H. Torrie. Principles and Procedures of Statistics. New York: McGraw-Hill Book Co., Inc., 1960, p. 106.

9. Ibid., p. 315.

10. Finney, D. J. Standard Errors of Yields Adjusted for Regression on an Independent Measurement. Biometrics Bulletin, 2:53-55, 1946.

11. Kendall, M. G. and A. Stuart. The Advanced Theory of Statistics, Vol. III, Chap. 42, "Tests of Hypotheses of Multivariate Analysis." London: Charles Griffin and Co., 1966.

12. Kramer, C. Y. Extension of Multiple Range List to Group Means with Unequal Number of Replications. Biometrics, 12:307, 1956.

13. Iampietro, P. F., R. F. Goldman, E. P. Buskirk, and D. E. Bass. Response of Negro and White Males to Cold. J. Appl. Physiol. 14:798, 1959.

14. Goldman, R. F. Energy Expenditure of Soldiers Performing Combat Type Activities. Ergonomics, 8:321, 1965.

15. Yarger, W. E., L. H. Cronau, Jr., J. S. Bird, and R. F. Goldman. Unpublished data, May 1968.

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Medical Field Research Laboratory Camp Lejeune, North Carolina	2a. REPORT SECURITY CLASSIFICATION **Unclassified** 2b. GROUP

3. REPORT TITLE

BODY ARMOR IN A HOT HUMID ENVIRONMENT. PART II: STUDIES IN HEAT ACCLIMATIZED MEN

4. DESCRIPTIVE NOTES *(Type of report and, inclusive dates)*

Interim report

5. AUTHOR(S) *(First name, middle initial, last name)*

William E. Yarger, LCDR MC USNR
B. D. Litt, A.M.
Ralph F. Goldman, Ph.D.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
January 1969	51	15

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. MF12.524	MF12.524.007-8008.2
c. Task No. MF12.524.007	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d. Work Unit No. MF12.524.007-8008	Vol. XIX, No. 1

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Bureau of Medicine and Surgery Navy Department Washington, D. C. 20390

13. ABSTRACT

The standard issue Marine Corps personnel body armor vest (M1955) was tested for its effect on men working under hot humid conditions approximating those seen in Southeast Asia. This vest is largely impervious to the passage of water vapor and thereby impedes evaporative cooling over the chest. Body armor produces a pronounced effect reflected by an increase in rectal temperature in the subjects when they are wearing the armor. This effect is restricted to a range of environment bracketed by 82 to 88°F WBGT (approximately). Below this level, heat loss from areas other than the chest is sufficient to dissipate body heat effectively. Above this range, the stress of the environment is so great and the evaporation of sweat is so inefficient that wearing body armor makes little difference. The effect of wearing armor in this range (82-88°F) is equivalent to a 5°F increase in the WBGT for unarmored men. The experiment was designed to eliminate the weight of the armor as a source of difference. (U)

UNCLASSIFIED
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Body Armor						
Acclimatization						
Environment, hot humid						
Heat Stress						